Swash Zone Dynamics: Modeling and Data Analysis

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LONG-TERM GOALS

The goals of the work are to develop improved predictive capability for non-linear time-dependent dynamics in the swash zone. The work involves numerical computations, comparison with field and laboratory results, and theoretical analysis. The focus of the project is to quantify net onshore-offshore swash zone properties from Computational Fluid Dynamics (CFD) experiments and to compare model predictions with field and laboratory data to evaluate theoretical models of swash dynamics

OBJECTIVES

1. Demonstrate capabilities of modeling non-linear interactions between incident and reflected waves on beaches using a Navier-Stokes model using the Volume of Fluid (VOF) method.

2. Conduct parameter studies, examining swash response (*e.g.*, bed shear stress, mean flow circulation, bore properties, run-up excursion length, *etc.*) to key physical parameters including beach foreshore slope, incident wave height, and wave frequency.

3. Develop a coupled fluid-sediment model to approximate sediment suspension and deposition and transport during swash events.

4. Interpret field data using insight gained from simulations with the VOF model.

5. Make a best attempt at simulating realistic swash zone events utilizing forcing conditions from observed time series of incident waves.

6. Examine model capabilities to test properties and predictions of simplified swash zone theoretical models.

APPROACH

The work involves theoretical development, numerical computations, and comparison with field and laboratory results. Scientific understanding of swash zone dynamics has advanced primarily by careful field measurement of wave and beach interactions. We have introduced additional complexity to mathematical modeling of the swash zone by solving the time-dependent equations representing conservation of mass and momentum for the physical situation of water waves shoaling on a sloping beach. To this end we have adapted a two-dimensional Navier-Stokes solver for free-surface air-water

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14. ABSTRACT
The goals of the work are to develop improved predictive capability for non-linear time-dependent dynamics in the swash zone. The work involves numerical computations, comparison with field and laboratory results, and theoretical analysis. The focus of the project is to quantify net onshore-offshore swash zone properties from Computational Fluid Dynamics (CFD) experiments and to compare model predictions with field and laboratory data to evaluate theoretical models of swash dynamics

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flows based on the Volume of Fluid (VOF) methodology (Hirt and Nichols, 1981) appropriate for simulations of the swash zone. This model has several advantages compared to current state-of-the-art swash zone models such as Rbreak (*e.g.*, Raubenheimer *et al*., 1995). Chief among these is the ability to represent non-linear breaking waves, depth dependency, and the ability to resolve the viscous bottom boundary layer, allowing estimates of the bed shear stress to be made. The model uses a control volume approach. The ability to handle a free surface is derived from allowing the control volumes to be full of water, empty (*i.e*., air), or partially filled. Fluxes of water are calculated at each control surface interface. If the volume of fluid (VOF) is full, and its neighboring control volumes are also full, then the standard continuum approximation (the Navier-Stokes equations) are solved in fairly standard discretized form, *e.g.,*

$$\nabla \cdot \vec{V} = 0,$$

and

$$\frac{\partial \vec{V}}{\partial t} + \nabla \cdot (\vec{V}\vec{V}) = \frac{-1}{\rho}\nabla \cdot p + \frac{1}{\rho}\nabla \cdot \tau + \vec{g} + \frac{1}{\rho}\vec{F}_b$$

where, ρ is the fluid density, p is pressure, τ is the viscous stress tensor, $\vec{F}_b$ is a body force (*e.g*., designed to force oncoming waves), and $\vec{g}$ is the acceleration due to gravity. When a control volume is empty of fluid, then, of course, constant (atmospheric) pressure is assumed. When a control volume is partially full, or when its neighbors are partially full, the methodology becomes more complex and force balances including surface stresses and inertial forces are approximated (sometimes involving projectile motion).

WORK COMPLETED

We have developed the VOF model and tested it in a series of idealized numerical experiments and against laboratory experiments we conducted at the Longshore Sediment Transport Facility (LSTF) (Figure 1.) at the Waterways Experiment Station, Army Corps of Engineers Laboratory in Vicksburg Mississippi.

Figure 1. LSTF showing waves, the instrumentation bridge, wave gages and ADV's.

RESULTS

Numerical simulations of inner surf and swash zone motions were carried out using both 1D (RBREAK2) and 2D (VOF) models (Figures 2-4). We find that the 2D model more accurately displays wave breaking and yields information regarding depth dependent fluid velocities in both the cross-shore and vertical direction. Comparisons with measurements showed that both models predicted the free surface elevation well (Figure 3), however more discrepancy was observed for swash velocities. The depth averaged velocity from the 1D model in the outer swash zone had the same magnitude as the measured near bed data, but did not closely match the measured velocity time series. The magnitude comparison yielded more evidence that the flow in the swash zone is depth uniform for most of the duration of the swash cycle except in a thin boundary layer. The velocities from the VOF model had the same magnitude as those from the measured velocity data during backwash, but had a large spike below the shoreward propagating bore that exceeded the measured data (Figure 4). Furthermore, the VOF velocity estimates show smaller lag/lead relationships compared to the measured data.

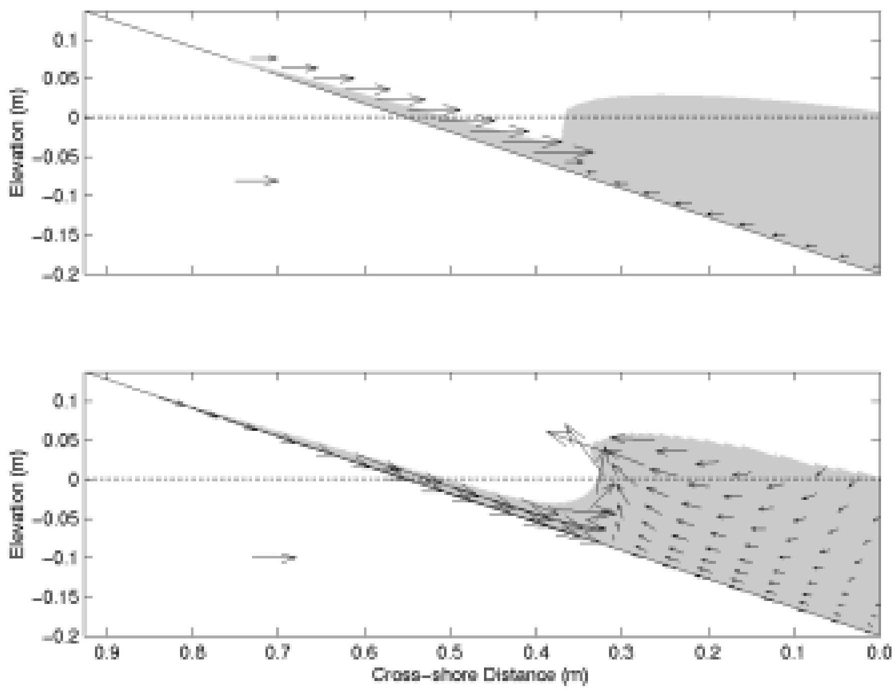

Figure 2: Flat beach (20°) simulations for RBREAK2 (upper) and VOF (lower). Vectors are depth-averaged (upper) and depth dependent (lower) fluid velocities. A 50 cm s^{-1} scale vector is shown in the lower left. Gray shading represents fluid in the model domain.

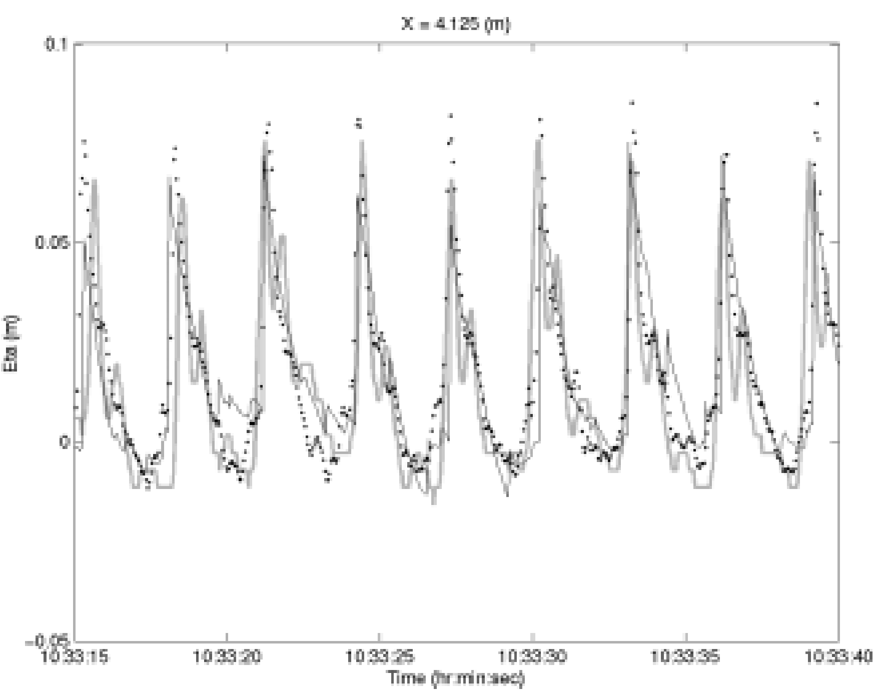

Figure 3: Sea surface comparison between ADV data (dots), VOF (gray), and RBREAK2 (black) in the inner surf zone.

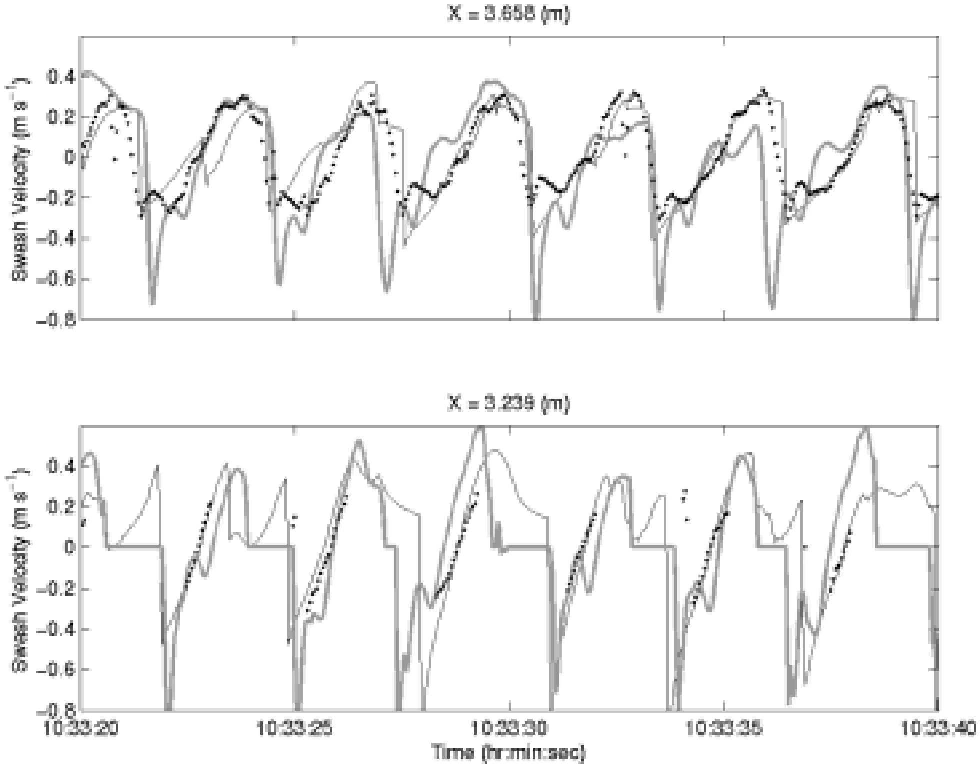

Figure 4. Velocity comparison for ADV (dotted), RBREAK2 (depth averaged; black) and VOF (gray). Upper panel is for outer swash zone and lower panel for middle swash zone. Negative velocities are onshore, positive velocities offshore.

Since the output from the 2 models was similar, one may ask, "What is the benefit to using a higher dimension model with increasing complexity especially when there is about a 70 fold increase in the required computation time?" Obviously it is a cost/benefit problem, but the 2D model is not restricted to shallow water environments and yields information as to the flow structure within the water column as opposed to being depth-averaged. Because of this information, one can now look into boundary layer structure, the time dependent nature of boundary layer formation over variable bathymetry and within the swash zone and ultimately begin to simulate time dependent bed shear stress (obtained from velocity profiles near the bed) across the nearshore profile. These processes *cannot* be extracted from a 1D model. These processes will in turn help to steer our knowledge of the important processes like wave breaking and propagation and potentially lead us to better methods for predicting sediment transport in the nearshore (where modeling capabilities severely lag those of nearshore hydrodynamics). Hence, we feel the benefit to using a model like VOF outweighs the cost.

The simulations performed here did not utilize the VOF model in its "out of the box" form and considerable work went into making the model appropriate for the surf and swash zones. However, more work needs to be done to tailor the model for nearshore hydrodynamics. Our future efforts will focus on incorporating a 2-equation turbulence closure scheme. The present model utilizes a constant eddy viscosity approach at present and we feel a 2 equation scheme such as the often used k-ε scheme will more accurately model the subgrid turbulence and may help in dissipating some of the high velocity spikes that were observed under the bore in the swash zone. Furthermore, this scheme will

enable a larger model domain with larger fluid volumes to be used such that the model can be forced from deep water allowing prediction of wave breaking, propagation, reformation, swash processes and boundary layer structure all from one model. Other ongoing work involves testing of various methods for forcing the model and the inclusion of tracer particles to visualize where and how sediment is transported during the breaking process and in the turbulent swash zone bore.

IMPACT/APPLICATIONS

Improved understanding of the swash zone has potential benefits for society in several areas. These include shore protection against beach erosion, understanding the behavior of shoaling waves and rip currents, mitigating problems associated with sediment transport, such as keeping waterways open for shipping in harbors, ports and inlets.

TRANSITIONS

The project began this year and we are testing and validating our model capabilities. The project has been joined by Jack Puleo, for his PhD dissertation, as part of the collaboration with NRL-SSC, who is adding the k-ε turbulence submodel and testing the model turbulent flow conditions.

RELATED PROJECTS

1. Dr. K. Todd Holland at the Naval Research Laboratory, Stennis Space Center, is leading the work on the laboratory and field experiments.

2. Dr. Britt Raubenheimer is working on swash zone measurements and theory under the ONR-YIP program.

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PUBLICATIONS

J.A. Puleo, T. Holland, D. N. Slinn, E. Smith, B. Webb, 2002, Numerical Modeling of Swash Zone Hydrodynamics, International Conference on Coastal Engineering, Cardiff, Wales.